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Aging of an Aluminum Alloy Resulting from Variations in the Cooling Rate

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The effect that the rate of cooling after solubilization exerts on the aging behavior of an aluminum heat treatable alloy was studied. Bars of the alloy were heated in a box furnace for solubilization, and after this was achieved they were cooled to room temperature by placing one end in a shallow tank of water. Thermal evolution along the bar was registered with the aid of thermocouples connected to a PC-based data logging system. Small samples were cut from the bars and aged for different times and temperatures. Results from microhardness tests indicate that peak hardness, at a given aging temperature, augments with the increase of the cooling rate until a certain value is achieved, above which the hardness remains constant. This feature was found to be due to precipitation taking place at the lower cooling rates.

Keywords aging, aluminum alloys, cooling rate, hardness, heat treating

1. Introduction

Heat treating is based on the possibility of controlling solid-state transformation reactions taking place during heating or cooling commercial alloys. Most of the reactions depend on the temperature/time path, and, due to their kinetic nature, it is possible to suppress or accelerate a given reaction by changing either the heating or cooling rate of the material (Ref 1). Heat treating of aluminum alloys rely on the possibility of achieving a supersaturated solid solution, which will improve the mechanical properties of the alloy as it ages (Ref 2-4). The steps involved are solubilization, quenching, and aging. Solubilization is conducted at a temperature high enough to put in solution the components of the alloy which, in the case of silicon and magnesium, is normally done at temperatures above 500 °C. Quenching is carried out either in cold water or, when distortion control is critical, in air or hot water (Ref 5).

The aging behavior depends on both the time and the temperature at which the treatment is made (Ref 2-4), since the mechanical properties of the material depend on the size and distribution of the precipitates formed. Another factor that affects this response is the rate at which the piece or part cools from the solubilization temperature, a feature associated with the amount of supersaturation attained in the alloy.

The aim of this article is to present the results obtained during the study of the aging behavior of an aluminum type 6063 alloy solubilized and then cooled at different rates by unidirectional cooling.

2. Experimental Procedure

An aluminum heat treatable type 6063 alloy (0.50Si-0.52Mg-0.21Fe-0.022Cu, in wt%) was supplied as bars 47.5 mm in diameter and 320 mm long. Small, 1.6 mm diam holes were drilled at different distances (measured from one of their ends) up to their center to introduce eight type K (chromel-alumel) thermocouples. The thermocouples were connected to a data logging system based on a PC computer (Ref 6), to record the thermal evolution during heating and cooling.

The bars were soaked for 4 h at 520 °C in a box furnace; then, one end of the bar was placed in a shallow tank of water, and the unidirectional cooling was recorded by the logging system. The bar was cut into eight 3 mm thick disks, each corresponding to the positions at which the thermocouples were introduced. These disks were sectioned into 5 mm square samples, which were aged at three different temperatures (130, 180, and 230 °C) for periods ranging from 20 min to 96 h. Vickers microhardness tests (500 g) were performed on treated and untreated specimens.

Unaged samples cut from the end introduced in water and from the position at which the farther thermocouple was located were analyzed by x-ray diffraction (XRD); aged samples cut from the portion submerged in water were also studied. All the measurements were done using Cu Kα radiation (λ = 1.54 Å, 45 kV, 40 mA, $\alpha_2/\alpha_1 = 0.5$).

The cooling and heating rates (dT/dt) were obtained by fitting an odd number of points into a series of successive quadratic polynomials and deriving at the central point (Ref 6) (except at the start and end of the data, since the initial and final portions of the curve were evaluated from a single polynomial).

It should be mentioned that the aging treatments were carried out after results from a conduction model, based on the explicit formulation of the finite difference method (Ref 7), indicated that the maximum difference in temperature between the center and a point close to the surface of the bar was less than 1 °C during cooling.

3. Results and Discussion

Figures 1 and 2 show the thermal evolution in one bar during heating and cooling; the distances indicated on the right-hand side of both figures correspond to the positions, measured from the end of the bar immersed in water, at which

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the thermocouples were located. No attempt was made to identify the different curves during heating (Fig. 1), although this was done on cooling (Fig. 2). Figure 3 shows the variation of the cooling rate (*dT*/*dt*) as a function of temperature for the positions identified as C and F (thermocouples placed 3.5 and 11.0 cm from the quenched end). The curves show that in both cases the rate of cooling first increases and then decreases, achieving a maximum cooling rate dependent on distance.

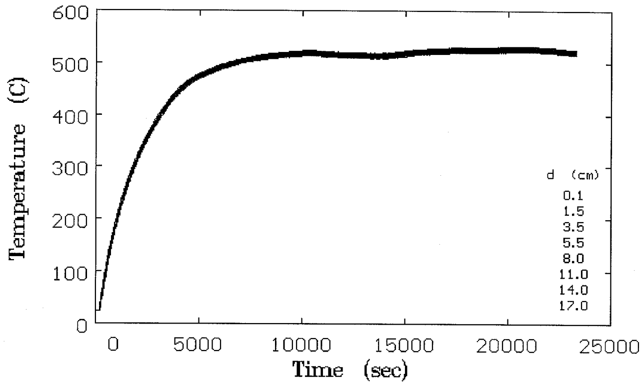

Fig. 1 Thermal evolution during heating

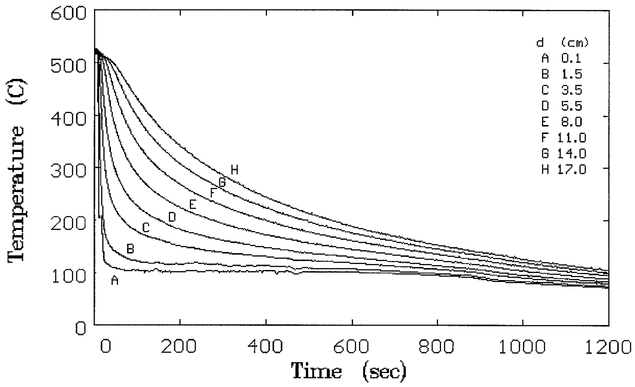

Fig. 2 Cooling resulting from placing one end of the sample in water

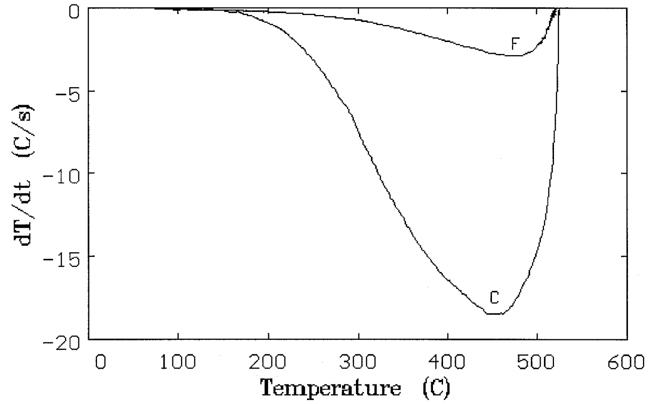

Fig. 3 Cooling rate as a function of temperature for two different positions

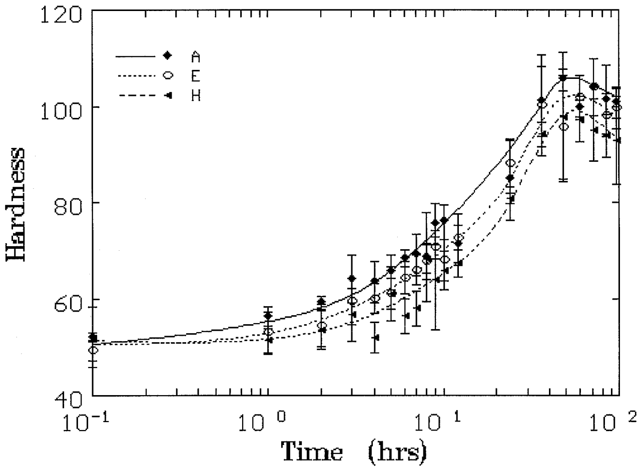

Fig. 4 Variation of hardness as a function of time for samples cut at different positions and aged at 130 °C

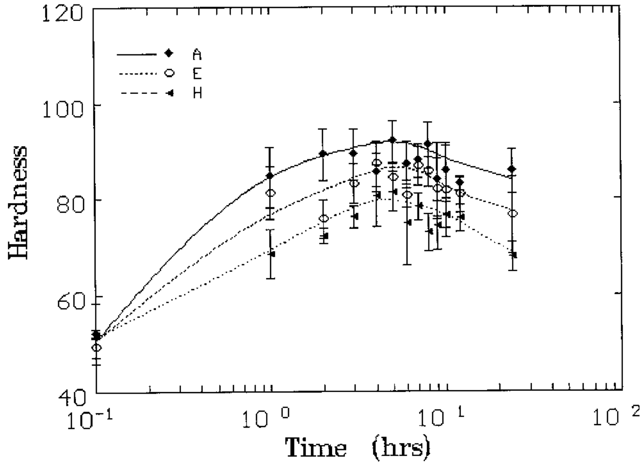

Fig. 5 Variation of hardness as a function of time for samples cut at different positions and aged at 180 °C

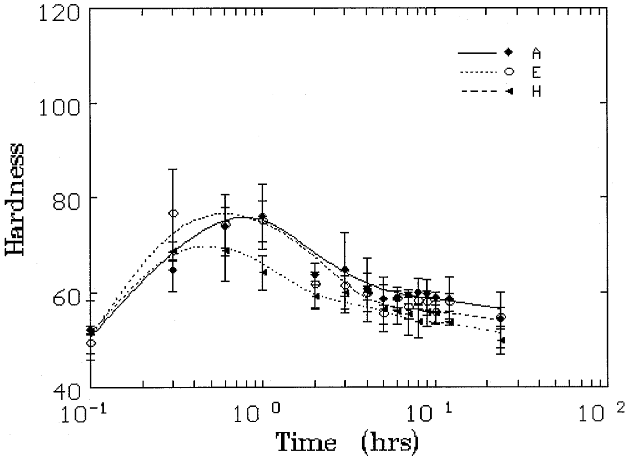

Fig. 6 Variation of hardness as a function of time for samples cut at different positions and aged at 230 °C

The aging behavior at 130, 180 and 230 °C for three different positions (A, E, and H) is shown in Fig. 4 to 6, and in Fig. 7 for samples cut from position A and aged at the three temperatures. All these figures describe the typical behavior of a precipitation-hardening alloy, in which hardness first increases up to a peak value and then decreases with time. As expected (Ref 8), the time at which the peak hardness is achieved increases as the aging temperature decreases, but also the hardness of the material augments as the aging temperature decreases, which corresponds to normal observed behavior (Ref 2-4).

Although the dispersion of the hardness measurements is high, it is possible to observe differences in the aging response from one position to another. This can be appreciated by plotting the peak hardness obtained at each temperature, independently of the time at which it was achieved, and the one measured on supersaturated samples as a function of cooling rate (Fig. 8). It can be seen in this last figure that the peak hardness achieved by the samples cut along the bar remains constant when the cooling rate is above 10 °C/s. When the cooling rate is reduced, or as the distance increases, the peak hardness decreases. The supersaturated samples exhibit a different behavior, since their hardness is lower in faster-cooled samples, which might be indicative of incipient precipitation during air cooling. Fractional softening (S) in treated samples as a function of cooling rate is plotted in Fig. 9. In this case, S was calculated as:

$$S = \frac{(H_m - H_i)}{H_m}$$

where H_m and H_i are the highest and individual hardness, respectively; in all cases H_m resulted to be that at the highest cooling rate. It is interesting to note, as was pointed before, that the material does not soften when it is cooled above 10 °C/s, a characteristic that was already pointed out in Ref 9 by authors who worked with different age-hardening alloys.

X-ray diffraction was carried out in four different samples, two of them supersaturated while the other two were treated to peak hardness and overaged. The untreated samples were cut from the region immersed in water (A) and cooled in air at the slowest rate (H) (see Fig. 2). Both treated samples were cut from position A. The XRD analysis indicated that the angular position (2θ) expected for the {311} planes was around 78.1° and, as can be seen in Table 1, it was not constant.

The difference in the angular position can be associated with the increase of internal stresses produced by precipitation of coherent particles (Ref 10). These positions were found to vary from 78.07 to 78.10° in supersaturated samples A and H. The angle increased to 78.16° in the peak-hardened A sample, and then it changed to 78.13° in the overaged sample. The difference of 0.03° (the accuracy of the measurement is 0.01°) between the supersaturated samples can be taken as an indication of precipitation during air cooling and will explain the reduction in peak hardness encountered in the samples cooled down at the lower rates, as well as the increase in hardness in unaged samples cut from these regions.

Table 1 Angular position (2θ) for the {311} planes

Sample, condition	2θ
A, supersaturated	78.07°
H, supersaturated	78.10°
A, peak hardness	78.16°
A, overaged	78.13°

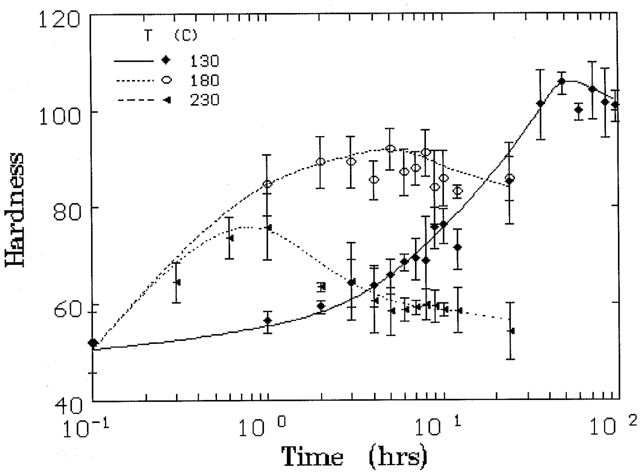

Fig. 7 Hardness measurements conducted on samples cut from position A as a function of time

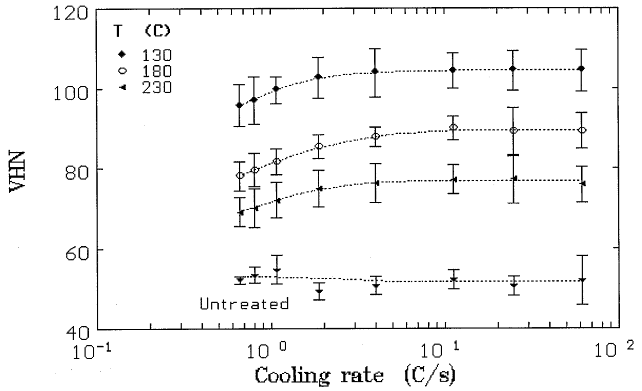

Fig. 8 Hardness in treated and untreated samples as a function of cooling rate

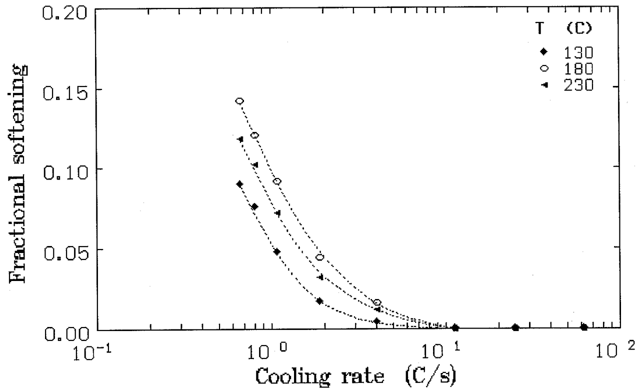

Fig. 9 Fractional softening in treated samples as a function of cooling rate

4. Conclusions

It is found that the aging behavior of a heat treatable aluminum alloy depends on the cooling rate, resulting in softer material when the rate decreases. It is observed that the peak hardness does not increase beyond a certain value once a critical cooling rate (which is around 10 °C/s) is achieved.

X-ray diffraction analysis indicates that the peak for the {311} planes is shifted to higher values as the degree of coherent precipitation increases. A small shift was also found in samples cut from the end introduced in water and the one left to cool in air, which can be related to precipitation while cooling.

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References

1. R.D. Doherty, *Physical Metallurgy,* R.W. Cahn and P. Haasen, Eds., 3rd ed., North Holland, 1983, p 933
2. H.K. Hardy, *J. Inst. Met.,* Vol 79, 1951, p 321
3. I.J. Polmear, Light Alloys, *Metallurgy of the Light Metals,* E. Arnold, London, 1980
4. C.R. Brooks, *Heat Treating,* Vol 4, *Materials Handbook,* ASM International, 1991, p 823
5. C.E. Bates, *J. Heat Treat.,* Vol 5, 1987, p 27
6. J.C. Morales, Ph.D. thesis, Universidad Autónoma de Nuevo León, 1995
7. M.G. Palafox, M.Eng. (Mat.) thesis, Universidad Autónoma de Nuevo León, 1996
8. J.W. Martin, *Micromechanisms in Particle-Hardened Alloys,* Cambridge University Press, 1980
9. C.E. Bates, *AFS Trans.,* Vol 91, 1983, p 1045
10. G. Kostorz, *Physical Metallurgy,* R.W. Cahn and P. Haasen, Ed., 3rd ed., North Holland, 1983, p 793